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GENERAL RELATIVISTIC X-RAY (UV) POLARIZATION ROTATIONS AS A QUANTITATIVE TEST FOR BLACK HOLES

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ABSTRACT

It is now 11 years since a potentially easily observable and quantitative test for black holes using general relativistic polarization rotations was proposed (Stark and Connors 1977, and Connors and Stark 1977). General relativistic rotations of the X-ray polorization plane of 10 to 100 degrees with X-ray energy (between 1 keV and 100 keV) are predicted for black hole X-ray binaries. (Classically, by symmetry, there is no rotation.) Unfortunately, X-ray polarimetry has not been taken sufficiently seriously during this period, and this test has not yet been performed. A similar (though probably less clean) effect is expected in the UV for supermassive black holes in some quasars and active galactic nuclei. Summarizing: (i) a quantitative test (proposed in 1977) for black holes exists; (ii) X-ray polarimetry of galactic X-ray binaries sensitive to at least 1/2% between 1 keV and 100 keV is needed (polarimetry in the UV of quasars and AGN will also be of interest); and (iii) proportional counters using timerise discrimination have been shown in laboratory experiments able to perform X-ray polarimetry and this and other methods need to be developed.

Measurement of the energy dependence of the direction of the plane of linear polarization of the X-ray emission from accreting black hole candidate binary systems will allow a direct and quantitative experimental test for the presence of a black hole in these systems (Stark and Connors 1977, Connors and Stark 1977, and Stark 1980). While classically there can be no continuous rotation of the plane of polarization with observed X-ray energy for such axisymmetric systems, general relativistic effects due to a black hole will result in an energy-dependent rotation of several tens of degrees in this polarization plane for energies between 1 and 100 keV which will provide a signature for the presence of a black hole. Measurement of this energy-dependent rotation, together with the corresponding general relativistic effects on the energy dependence of the net observed degree of linear polarization of the X-ray emission, will allow us to test whether a black hole is present and to quantitatively measure the spin of the black hole, as well as to probe the geometry of the accretion process.

The reason that the X-ray polarization properties are so sensitive to the strong gravitational field of the black hole, comes from the fact that the rotation of the plane of polarization of the X-rays propagating from the accreting gas near the black hole to the observer is of the same order as the amount of gravitational bending which these rays undergo. (The radiation is polarized because of electron scattering and other processes occuring during the radiative transfer within the gas surrounding the black hole.) Since, for a black hole, this bending can amount to 10 to 100 degrees, similarly large general relativistic polarization rotation effects will exist. These polarization effects are therefore intimately related to one of the most well known effects of gravitation: that of light bending — but are measured in tens of degrees rather than the usual seconds of arc!

Detailed calculations (Stark and Connors 1977, Connors and Stark 1977, and Stark 1980), for the X-ray polarization properties of the standard black hole disk model, show rotations of 10 to 100 degrees in the direction of the net observed plane of linear polarization with X-ray energy between 1 and 100 keV, (Fig.1). The magnitude of these polarization rotations becomes bigger with increasing angular momentum of the black hole and for decreasing observer polar angles. Typically we find for energies between 1 and 100 keV a polarization angle rotation of 40 degrees in the X-ray emission from accretion onto a nonrotating Schwarzschild black hole and 90 degrees for accretion onto a maximally spinning Kerr black hole. General symmetry arguments do not allow such continuous polarization rotations with energy for classical (*i.e.*, weak gravitation), axisymmetric systems, so that detection of this unique polarization feature can indicate both the existence of a black hole, and that the accretion is in the form of a disk all the way to the inner region. A similar behaviour of the plane of polarization with energy is also expected from most other disk models which have strongly radially dependent physical conditions. General relativistic effects will also modify the X-ray energy dependence of the degree of linear polarization (Fig. 2) — it being reduced typically by a factor of 2 from the classical result.

Detailed calculations (Connors and Stark 1977; Connors, Piran, and Stark 1980; Stark 1980) have also been performed for other black hole accretion models: standard disk models for the outer region and an optically thin inner disk region or a geometrically thick cloud surrounding the black hole. For these types of accretion, we expect the polarization properties to follow the standard disk results for low energies (up to 1 to 10 keV), while above these energies, the polarization properties become energy-independent with a plane of polarization differing from the lower energies by an angle different from 90 degrees (the classical result; Lightman and Shapiro 1975). Observation of a continuous rotation of the polarization angle with X-ray energy at low energies, followed by a jump different from 90 degrees, would indicate the existence of a black hole and that the accretion in the inner region is optically thin. Further information would be obtained from the energy dependence of the degree of linear polarization. Monte-carlo calculations of the effects of a large cloud of scattering material surrounding the binary system show that these general relativistic rotations would remain observable even for optical depths of scattering material up to 0.5 (Connors, Piran, and Stark 1980; and Stark, 1980).

As well as observing the energy dependence of the plane and degree of X-ray polarization, one may also expect long-term, temporal variations in these polarization properties at a fixed observer energy. Observers may detect changes in the plane and degree of X-ray polarization if the size of the accreting cloud or disk varies, giving rise to a general relativistic time-dependence of these polarization properties. Such changes could be associated with spectral and intensity changes. In particular, it would be important to see if there are any temporal changes in the polarization features of Cygnus X-1 which are correlated with the spectral intensity changes between the two states of this source.

X-ray polarization observations would be able to rule out nongeneral relativistic contributions to this rotation of the polarization plane with X-ray energy. A twisted nonaxisymmetric disk, resulting from the nonalignment of the spin axis of the black hole with that of the binary system, could lead to such a rotation. This possibility is unlikely, however, since general relativistic dragging of inertial frames effects are expected to align the X-ray emitting inner region of the disk into the equatorial plane of the black hole (Bardeen and Patterson 1975). Any remaining

effects from a twisted disk could be discovered observationally (and distinguished from general relativistic rotations) by looking for a time-dependence of the polarization properties with a period equal to that of the orbital period of the binary system. A second additional source of energy-dependent polarization rotation at low X-ray energies (on top of the general relativistic rotation) would occur from Faraday rotation if a strong homogeneous magnetic field is present. A more likely magnetic field configuration, because of the differential rotation present, would be a chaotic field which would influence the degree and not the plane of polarization. In any case, even for the maximum magnetic field possible, these magnetic effects would only be significant below 1 to 10 keV, and they would be observationally distinguished from general relativistic effects by the E^{-2} dependence of the magnetic depolarization with energy E (Gnedin and Silant'ev 1977). The measurements of Long, Chanan, and Novick (1980) of 3% linear polarization in Cygnus X-1 at 2.6 keV, if positive, suggest that such depolarization does not take place in this source.

What difference can we expect between a black hole and neutron star? The difference in surface boundary conditions and magnetic fields can be expected to lead to observationally distinct polarization properties between a black hole as opposed to a neutron star X-ray binary. (In general, we would expect neutron star binaries to be more highly polarized.) If, however, we assume a nonmagnetized neutron star and neglect the difference in boundary conditions, then we can estimate a factor of ~5 difference between the general relativistic polarization rotations for a Kerr black hole and that for a neutron star, and a factor of (1 to 2) between a Schwarzschild black hole and neutron star. Experimentally we would look for a statistical correlation between X-ray binaries with high mass compact objects (indicating black holes) and those showing the larger polarization rotations. Further evidence would be given by the energy dependence of the degree of polarization.

In laboratory experiments, Sanford, Cruise, and Culhane (1970) have demonstrated the ability to use timerise discrimination in proportional counters to perform X-ray polarimetry. The charge cloud of cascade electrons has a shape dependent on the polarization of the X-ray photon inducing the photoelectron process. As the cloud drifts toward the anode, the shape determines the timerise characteristics of the signal and hence the incoming polarization can be measured. This method seems to show great promise and it is surprising that it has not been exploited more. (Above 30 keV to 50 keV, where the photoelectric opacity drops, a compton polarimeter would probably be necessary.)

Similar general relativistic effects can be expected for supermassive black holes. The magnitude of the general relativistic polarization rotations remains the same independent of the black hole mass. The mass simply determines where in energy the rotation takes place. Thus, for disk accretion about a supermassive black hole (mass $5 \times 10^8 M_{\odot}$) rotations of 10 to 100 degrees can occur (when free-free opacity and Faraday effects are not dominant) in the UV, beginning around 10 to 20 eV (Stark and Connors 1988). (Polarization swings with timescales of hours to days from orbiting hot spots may also be observable; Connors, Piran, and Stark 1980; and Stark 1980.) Black hole accretion is a possible model for quasars and some active galactic nuclei, and it would be of great interest to have accurate polarimetry of these objects at these frequencies. Observations of a UV excess in the flux of some quasars have already allowed an estimate of the disk contribution and hence estimates of the black hole mass and accretion rate (*e.g.*, Malkan 1983). Knowing the mass and accretion rate, a definite prediction for the general relativistic polarization

rotation and degree of polarization as a function of frequency can be made (Stark and Connors 1988). Unfortunately, accurate polarimetry at these frequencies does not presently exist in order to make a comparison with these theoretical predictions. It should be noted, though, that model-dependent details are much more uncertain in the supermassive case as compared to the galactic X-ray binary case. X-ray polarimetry of X-ray binaries is thus preferred over UV quasar observations as providing the cleanest quantitative test for black holes.

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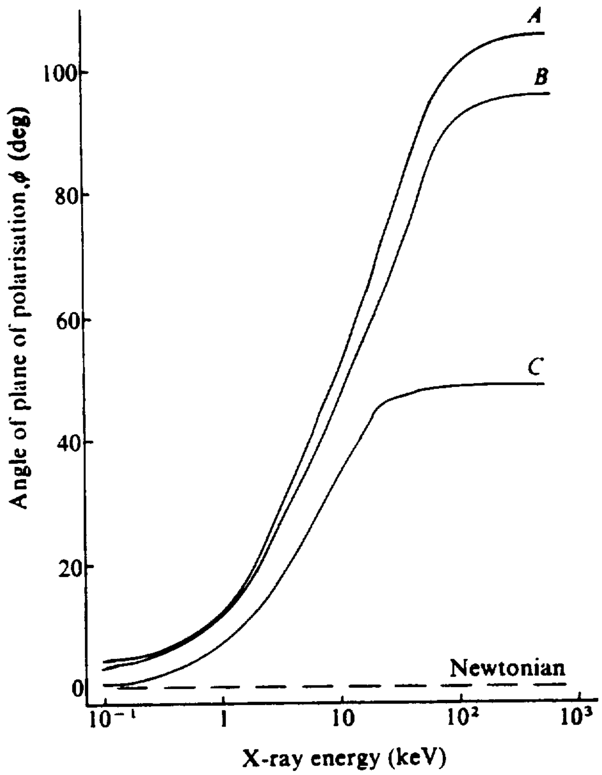

FIG. 1.—Variation of plane of polarisation with energy for $\theta_0 = 41.1$ for the one-temperature model with *A*, $a/m = 0.9981$; *B*, $a/m = 0.9$; C, $a/m = 0$, where viscosity parameter, $\alpha = 0.1$; mass of black hole, $M = 9M_{\odot}$; mass accretion rate $= 7 \times 10^{17}$ gs^{-1}.

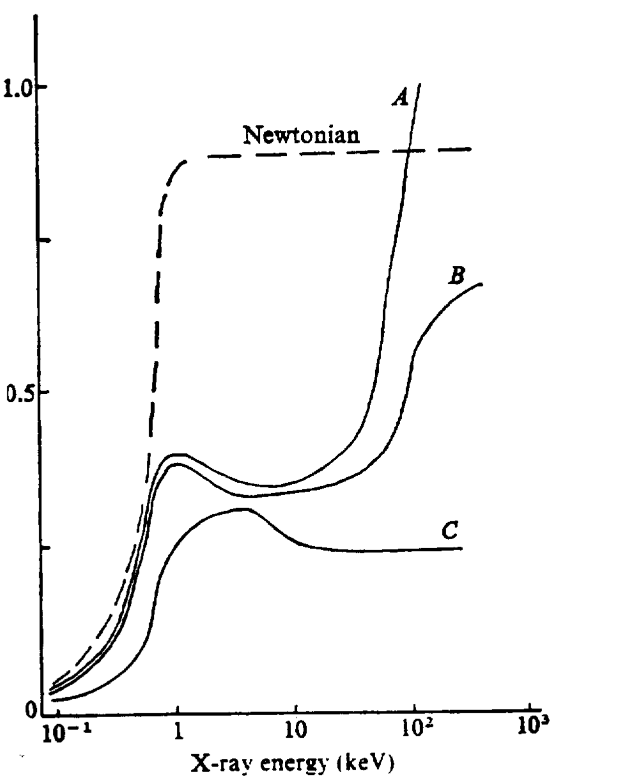

FIG. 2.—Variation of linear polarisation with energy for the one-temperature model, with *A*, a/m = 0.9981; *B*, $a/m = 0.9$; C, $a/m = 0$. Same parameters as Fig. 1.

DISCUSSION

SHAPIRO: It was not clear to me that the distinction between black holes and neutron stars would be so simple to make reliably. Could you comment in more detail on the means for such distinctions?

STARK: The pick-out (both radially and azimuthally) of the most blue shifted rays which are the dominant contribution to the polarization rotations (see Stark & Connors, 1977) allows us to estimate the size of the polarization rotations for neutron stars. (Neglecting, for the moment, the surface boundary differences). Comparing the general relativistic rotations (with X-ray energy) from fairly extreme neutron stars with the black hole results (for the same observer angle) we find a factor ~ 5 difference between a maximal Kerr black hole and a neutron star, and ~1-2 between a Schwarzschild black hole and a neutron star. There is a clear distinction between a rapidly spinning black hole and a neutron star; but less so for a Schwarzschild black hole. The X-ray polarization properties of neutron stars can, however, be expected to be also observationally distinct from black holes because of the radiative differences in the inner regions arising from surface boundaries and magnetic fields. (Higher degrees of polarizations can be expected from neutron stars). The energy dependence of the degree of polarization together with that of the polarization rotations may allow us also to distinguish between Schwarzschild black holes and neutron stars, if this is true. It will also be important to correlate X-ray polarization data with other observations. Thus, we will expect to see statistically higher X-ray polarization rotations with energy in those binaries which have higher mass compact objects (those beyond the neutron star mass limit, and therefore black hole candidates).

HELLINGS: Is the width of the x-ray spectrum sufficiently narrow that you can pick out the shift of frequency.

STARK: I'm not sure I exactly understand the question. The polarization rotation test has no direct relation to frequency shifts. The polarization measurements are performed on the continuum X-ray flux and have nothing to do with any particular spectral features.